AN ADVISORY ON PREPARATION OF HEAT MAPS FOR CITIES

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GIZ is responsible for the content of this publication.

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List of Abbreviations

CRCAP	Climate Resilient City Action Plan
CSCAF	ClimateSmart Cities Assessment Framework
DN	Digital Number
GIS	Geographic Information System
GIZ	Gesellschaft für Internationale Zusammenarbeit
HTML	Hypertext Markup Language
ICCCS	International Conference on Communication, Computing & Security
ICLEI	International Council for Local Environmental Initiatives
IR	Infrared
IT	Information Technology
LST	Land Surface Temperature
MoHUA	Ministry of Housing and Urban Affairs
NASA	National Aeronautics Space Centre
NDVI	Normalized Difference Vegetation Index
NGO	Non-Governmental Organization
NH	National Highway
NIR	Near Infrared
OLI	Operational Land Imager
QGIS	Quantum Geographic Information System
TIRS	Thermal Infrared Sensor
TM	Thematic Mapper
TOA	Top of Atmosphere
UCM	Urban Canopy Model
UHI	Urban Heat Island
ULB	Urban Local Body
USGS	United States Geological Survey
WRF	Weather Research and Forecasting
WRI	World Resources Institute

List of Figures and Table

1 Introduction

Land use and land cover change contribute to various highly critical environmental phenomena that need to be periodically analysed for studies related to environmental conservation, resource management, land use planning, or even climate change monitoring. Urban growth patterns and the ratio of green to build space often have a huge impact on the Land Surface Temperature (LST). LST is the measure of heat emission from land surface due to various activities associated with the environment. For instance, an increase in paved land cover is an indication of concentrated human activities, which often leads to increased LST (Ramachandra, Aithal, & Durgappa, 2012). The increase in the average temperature of the area as compared to its surroundings give rise to the urban heat island (UHI) phenomenon. The temperature rise is usually more evident during night times than that of the day owing to greater differences in temperature. Tarmacked roads and concrete buildings that absorb sunlight and then radiate the heat intensify heat traps and thus heighten the overall temperature of the area. Therefore, with rapid growth of cities, the threat posed by UHIs has also increased significantly. Some of the direct adverse effects of UHI include various illnesses like dehydration, heat strokes, etc., and numerous environmental impacts such as forest fires, air quality degradation, etc. significantly impacting the mortality rate of urban residents. Additionally, the indirect impacts involve burdening of health services, shortage of water and electricity, infrastructural damage among others (TARU, 2021) deeply straining urban economics.

While cities struggle to cope with the rise in urban demands, it is important for decision makers to take note of surface temperature changes that also aggravate climate change impact. This document outlines steps to be followed by city planners and policymakers to generate LST maps for their respective areas of interest. Furthermore, it elaborates how these maps can inform action on the ground and aid in evidence-based planning. A set of guidelines that are to be followed before and during the LST generation along with representational tips for easy decoding of the LST maps has been the intent of this document. The determination of hotspots within urban areas can allow urban practitioners to prioritise and deploy area-based interventions and landscape guidelines to nullify the impact of UHIs. Further local adaptation techniques can contribute in account of global climate change adaptation measures and goals set by various international and national organisations.

Advanced remote sensing techniques for LST retrieval can be very useful to identify urban heat island phenomenon. There are a number of approaches to retrieve LST from high to medium spatial resolution remote sensing data using thermal infrared (IR) spectrum. After carefully selecting LandSat 5 or LandSat 8 imagery based on the least cloud cover criterion, one of three possible algorithms can be chosen for LST extraction. On the data processing front, any platform that can handle raster data such as ArcMap, ArcGIS Pro, QGIS, and Google Earth Engine, etc. can be used.

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This advisory report details the process of LST retrieval using thermal band (Band 10) of LandSat 8 imagery. In summary, the process involves calculating Top of Atmosphere (TOA) spectral radiance to compute brightness temperature. Additionally, one needs to calculate NDVI to subsequently decipher the land surface emissivity. LST is then calculated using emissivity and brightness temperature based on the formulae explained in Section 3 of this report. LST hotspots adversely affect the microclimate of cities and countering their negative impacts should be a priority for city administrations. The best way to do so is via establishment of urban green-blue spaces that dampen the impact of UHIs. Mitigating the effects of these hotspots will be a small but critical step towards countering climate change.

2 Prefatory Guidelines

2.1 Selection of Images

For calculating LST, satellites that record reflectance in thermal infra-red wavelength are required. Not all multispectral satellites provide reflectance in thermal infrared bands. For instance, while LandSat 8 has thermal bands, Sentinel 2 does not and hence images from Sentinel 2 satellite cannot be used. Moreover, LandSat 7 data also might not be very useful as it has been reported to contain scan line errors since the year 2003. However, LandSat 5 data may be used as it has the Thematic Mapper (TM) sensor which may yield the desired results in calculating LST. Most widely utilised and publicly available sources for LandSat imagery are the United States Geological Survey's (USGS)[1] LandSatLook Viewer[2], GloVis: The Global Visualisation Viewer[3] and USGS Earth Explorer[4].

The above-mentioned platforms can be easily accessed on a generic web browser and also offer a custom search of the LandSat data based on the region of interest (point or polygon), dates of interest, and other parameters such as cloud cover, path, row, etc. For standardisation of data, it is advised to limit imagery procurement from a single satellite. However, while selecting these satellite images, it is also important to acquire cloud/ haze free images as clouds block the view of ground as well as the areas under haze. Besides, cloud shadows could yield underestimates for land surface temperature.

2.2 Available methods and platforms

To process the data, platforms such as ArcMap, ArGIS Pro, QGIS, Google Earth Engine and even programming languages like Python or R can be used. Although this advisory report focuses on retrieving information from the Thermal infrared band of LandSat 8, the methods mentioned below can be used to generate LST from band 6 of the Thematic Mapper (TM) sensor (LandSat 5) as well. Possible algorithms that can be chosen for the study include:

- Radiative transfer equation using in-situ radio-sounding data (Sobrino, Jimenez-Munoz, & Leonardo, 2004).
- Mono window algorithm developed (Qin, Karnieli, & Berliner, 2001).
- Single channel algorithm (Jimenez-Munoz & Sobrino, 2003).

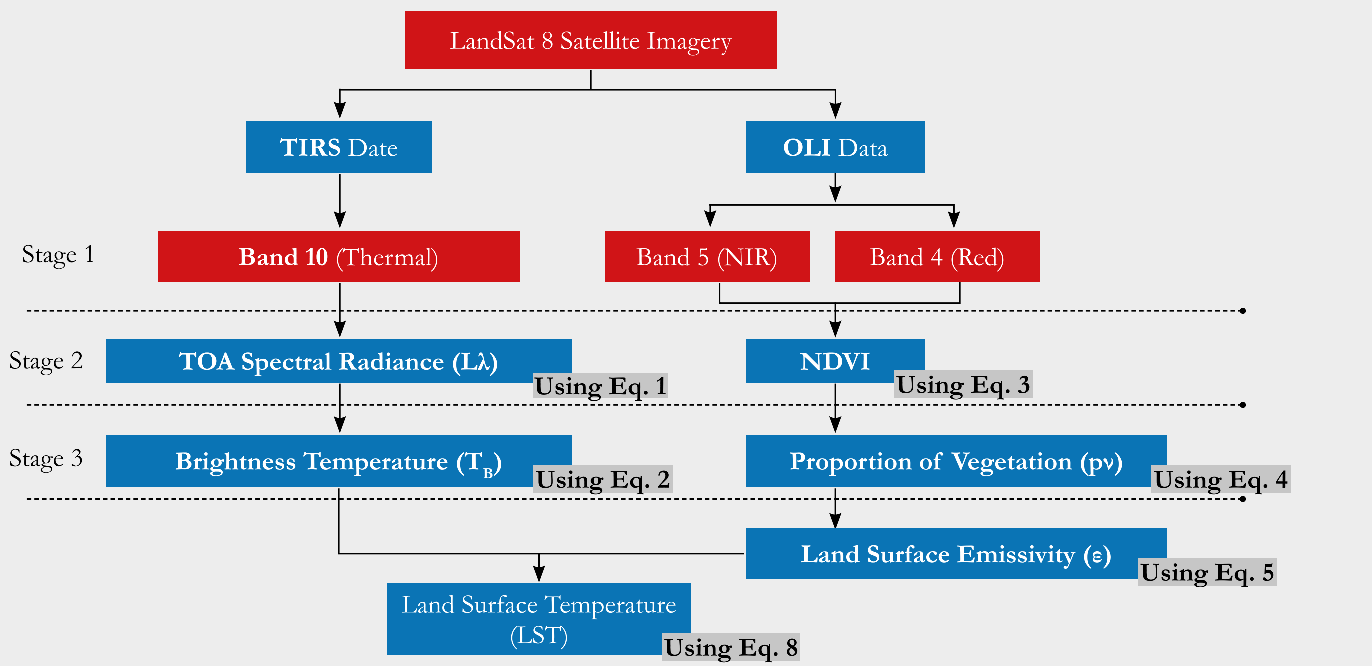
[1] LandSat Science, National Aeronautics Space Centre (NASA). https://LandSat.gsfc.nasa.gov/data/where-get-data
[2] LandSatLook, United States Geological Survey (USGS). https://LandSatlook.usgs.gov/
[3] Global Visualization Viewer (GloVis), United States Geological Survey (USGS). https://glovis.usgs.gov/
[4] Earth Explorer, United States Geological Survey (USGS). https://earthexplorer.usgs.gov/

3 Methodology

3.1 Method Flowchart and description

This section outlines the methodology to use satellite imagery in the extraction of LST and is primarily derived from acclaimed research that uses LandSat 8 (Guha, Govil, Dey, & Gill, 2018) band 10 for surface temperature. The equations were coded in Google Earth Engine but as mentioned above, one can use other platforms to achieve the same results. Overall, the process is divided into 3 stages. The first stage involves the use of TIRS data and Band 10, the second stage involves the use of OLI data and Bands 4 & 5, while the third stage involves the use of the LST equation which includes variables from both stages to calculate LST itself. The method flowchart is presented in Figure 1 and steps to be followed under each stage are detailed in the following text.

Figure 1. Methodology for LST retrieval from LandSat 8



[5] Google Earth Engine is a cloud-based platform that makes it easy to access high-performance computing resources for processing extensive geospatial datasets, without having to suffer the IT pains currently surrounding either. Additionally, and unlike most supercomputing centres, Earth Engine is also designed to help researchers quickly disseminate their results to other researchers, policymakers, NGOs, field workers, and even the general public. Once an algorithm has been developed on Earth Engine, users can produce systematic data products or deploy interactive applications backed by Earth Engine's resources, without needing to be an expert in application development, web programming or HTML.

Stage 1

Thermal Infrared Sensor (TIRS) Data from the LandSat 8 image

1. Select Band 10 raster which records reflected light in the Thermal Infrared wavelength range.

2. Calculate the *Top of Atmosphere (TOA) Spectral Radiance* (in $Wm^{-2}sr^{-1}mm^{-1}$) which is the amount of reflected light being recorded by the satellite sensor. It is calculated using the equation below.

$$L\lambda = 0.0003342 * DN + 0.1 \quad \textbf{Eq. (1)}$$

   Where, DN is the digital number value for the quantized and calibrated standard product pixel of band 10 and 0.0003342 and 0.1 are the constants.

3. Calculate the *Brightness Temperature* which is the radiance of the microwave radiation travelling upward from the top of the atmosphere to the satellite. The equation is as follows and uses the spectral radiance calculated above:

$$T_B = \frac{K_2}{\ln((K_1/(L\lambda))+1)} \quad \textbf{Eq. (2)}$$

   Where, K_1 and K_2 are the calibration constants mentioned in the Table 1:

Table 1. Calibration Constants used in Eq. (2)

Thermal Constant	Band 10
K_1	774.89
K_2	1321.08

Stage 2

Operational Land Imager (OLI) data from the LandSat image

1. Select Band 4 and Band 5 rasters in LandSat 8 satellite image which record the reflected light in the red and near-infrared wavelength ranges respectively.

2. Calculate the *Normalised Difference Vegetation Index (NDVI)* from these two rasters. NDVI is a ratio that ranges from -1 to 1 with higher values indicating higher vegetation, values close to 0 indicating barren land and negative values indicating water bodies. Healthy vegetation reflects more infrared light and absorbs light in the red wavelength. This means the value of a pixel in Band 4 corresponding to an area of high vegetation will be very low while that of the same pixel in Band 5 at the same spot will be high. The equation to calculate NDVI is as follows:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \quad \textbf{Eq. (3)}$$

   Where, NIR and Red are Band 5 and Band 4 of the LandSat 8 imagery respectively.

3. The next step is to calculate the Proportion of Vegetation as follows:

$$P\nu = \left[\frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}\right]^2 \quad \textbf{Eq. (4)}$$

   Where, NDVI is the Normalised Difference Vegetation Index from Eq. (3), $NDVI_{min}$ and $NDVI_{max}$ is the minimum and maximum NDVI of the LandSat scene respectively.

NDVI has been adopted by many cities to evaluate "urban greenness". This provides cities with information on the environmental and health quality of cities' green areas along with the quantitative estimation of proportion of green spaces in relation to other urban land cover types (Abutaleb, Freddy, Nkongolo, & Newete, 2020). Besides, the research on urban agricultural and green cover needs, NDVI (vegetation analysis) can also be used to determine mitigation and protection strategies against unfortunate natural calamities providing evidence based on trends and scope of humanitarian aid during such catastrophic events (Bhandari, Kumar, & Singh, 2012).

4. *Land Surface Emissivity* is calculated using the equation:

$$\varepsilon = 0.004 * Pv + 0.986 \quad \textbf{Eq. (5)}$$

Where, Pv is the proportion of vegetation from Eq. (4) and the constants (0.004 and 0.986) are calculated using:

$$d\varepsilon = (1 - \varepsilon_s)(1 - Pv)F\varepsilon_v \quad \textbf{Eq. (6)}$$

$$\varepsilon = \varepsilon_v Pv + \varepsilon_s (1 - Pv) + d\varepsilon \quad \textbf{Eq. (7)}$$

Where, dε is the effect of the geometrical distribution of the natural surfaces and internal reflections, ε_s is soil emissivity whose value is highly variable and as such, the mean value of this constant from the ASTER spectral library can be chosen. ε_v is vegetation emissivity (empirical constant with a value of 0.99), Pv is fractional vegetation (or proportion of vegetation) calculated in Eq. (4) and F is a shape factor whose mean is 0.55 (empirical constant).

Stage 3

Getting the final Land Surface Temperature (LST) raster

1. The final LST is calculated using the equation:

$$LST = \frac{T_B}{1 + (\lambda \sigma T_B / (hc))\varepsilon} \quad \textbf{Eq. (8)}$$

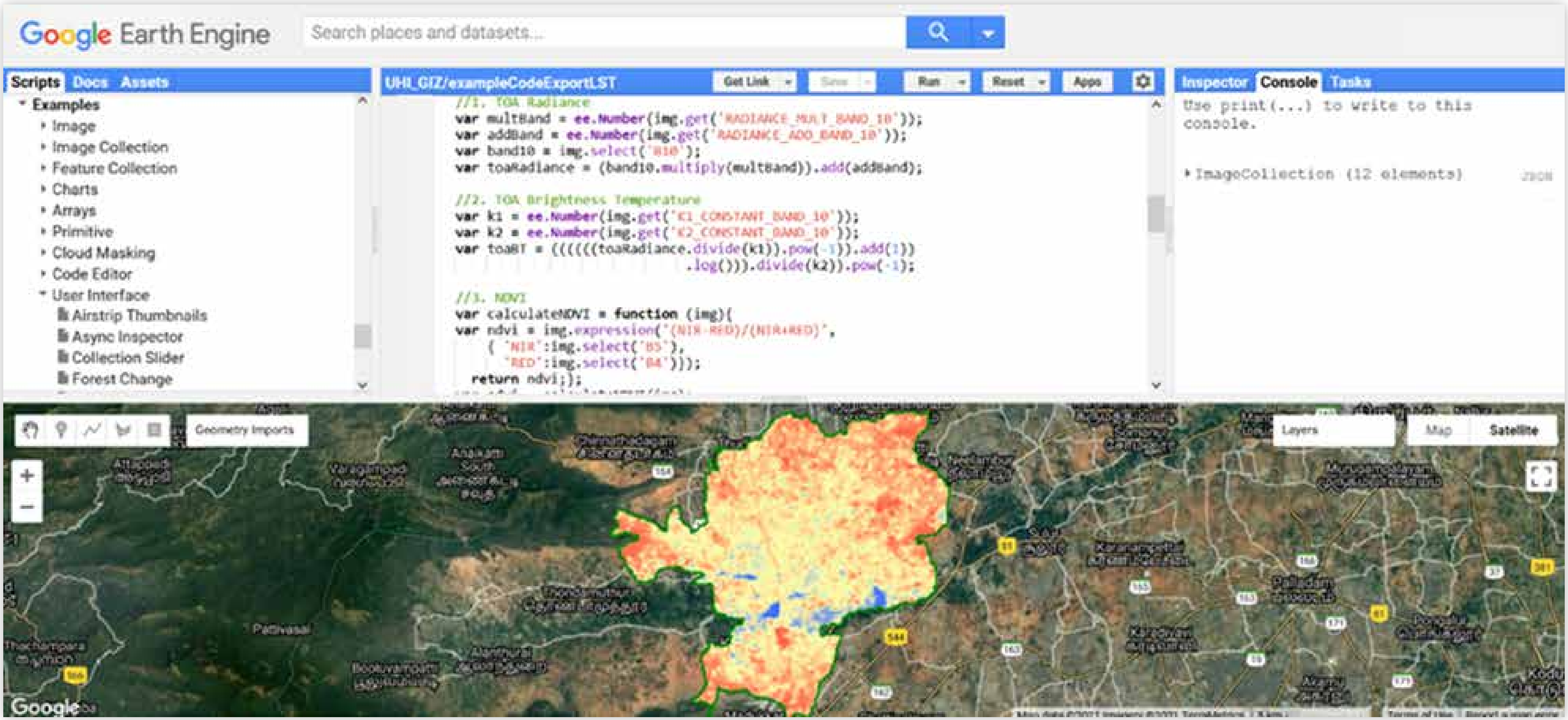
Where, λ is the effective wavelength (10.9 mm for band 10 in LandSat 8 data), σ is Boltzmann constant (1.38 × 10−23 J/K), h is Plank's constant (6.626 × 10−34 Js), c is the velocity of light in vacuum (2.998 × 10−8 m/sec), T_B is brightness temperature from Eq. (2) and ε is emissivity from Eq. (7).

2. This value of **LST** can be converted from Kelvin **(K)** to degree Celsius **(°C)** using the equation:

$$LST\ (°C) = LST\ (K) - 273.15 \quad \textbf{Eq. (9)}$$

Figure 2 shows the interface of the interactive Earth Engine platform and example output of the LST algorithm executed in the platform.

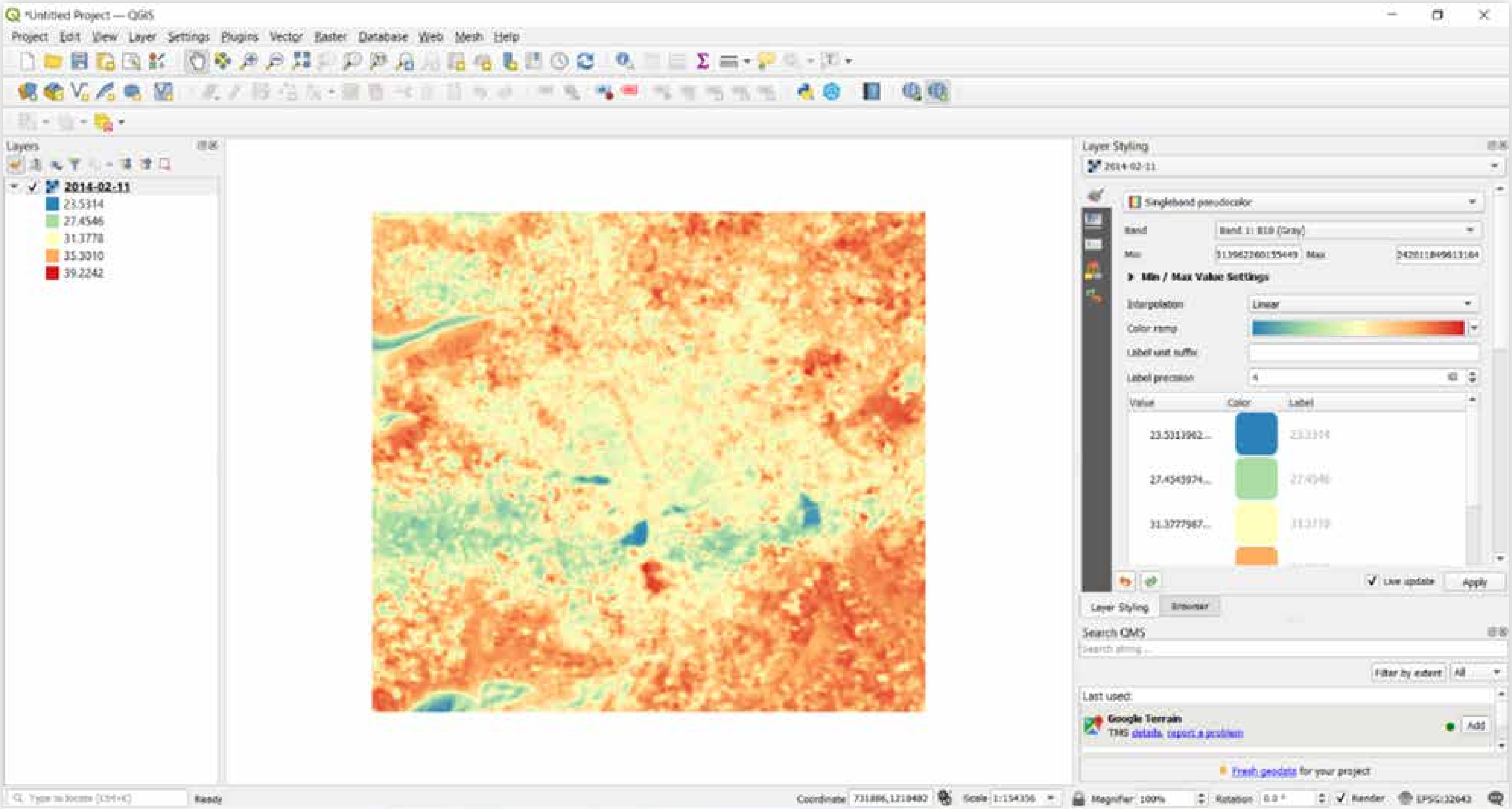
Figure 2. Sample output of the LST algorithm in Google Earth Engine interface



3.2 Guidelines on making inferences from the visualizations

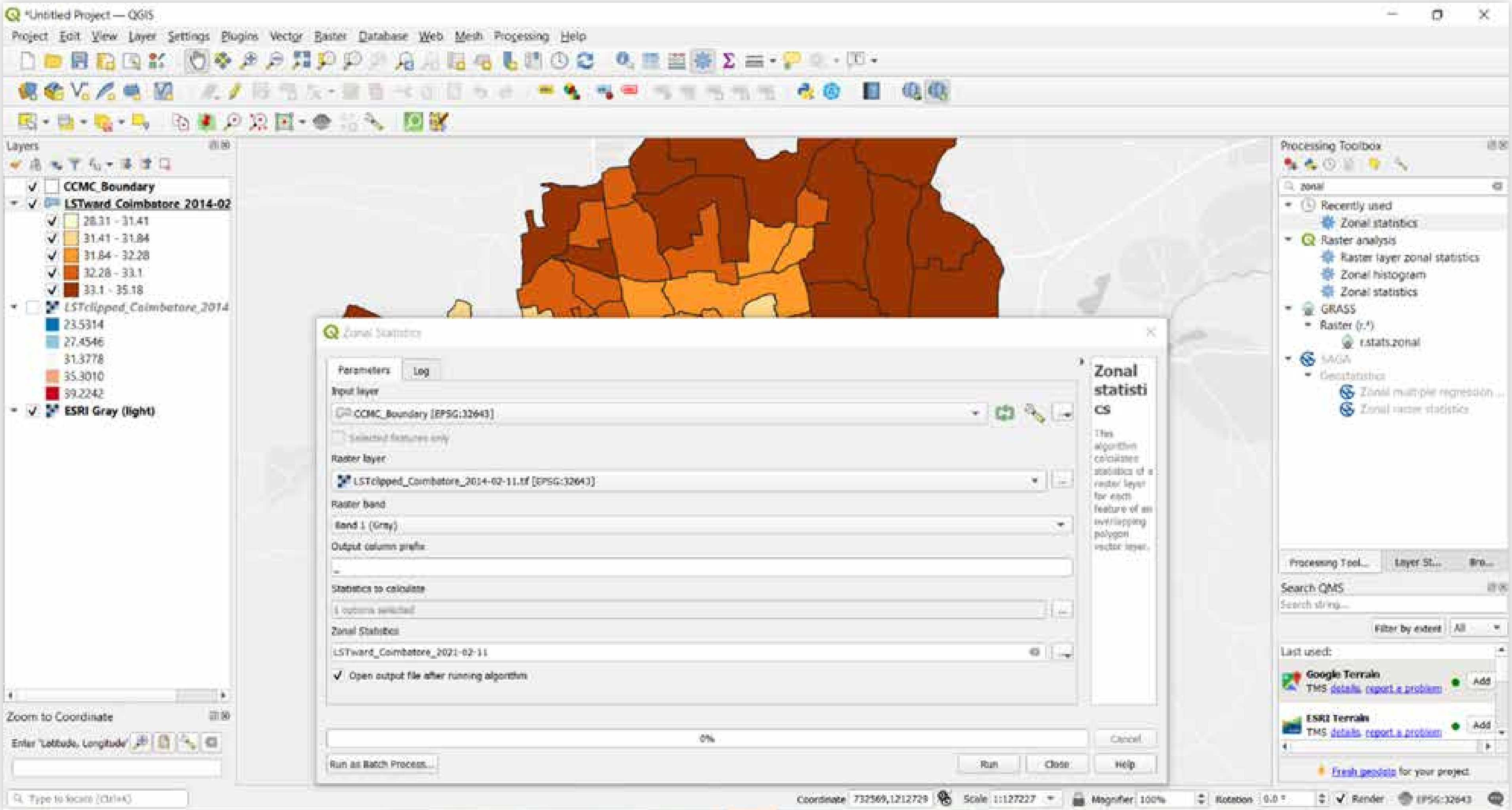
The resultant LST image derived from Eq. (9) should be imported into a GIS platform, where minimum–maximum stretching can be used to visualise the gradation of surface temperature throughout the study region. The colour scheme for the LST image(s) can be such that cool colours (blue, green, etc.) are used for a lower range of LST values and warm colours (red, orange, etc.) are used for LST values higher than the average surface temperature of the sampled area and season. Figure 3 shows an example of an applied single-band pseudocolour scheme to visualise the image in different colours.

Figure 3. Pseudocolour visualisation for Land Surface Temperature imagery



Furthermore, a range mask or a value mask can be applied to the LST image to only visualise regions pertaining to the peculiar values such as hotspots or coldspots, for example- create a mask of 26°C to aggregate all the regions where LST is 26°C or higher. Zonal statistical analysis can also be performed for zone-wise LST analysis. However, this method would require two input layers, i.e., LST image and the ward boundary or sub-district boundaries' polygon vector files for results. Statistics such as 'minimum', 'maximum' and 'mean' can then be extracted and attached zone-wise from the LST layer to the vector files. Figure 4 below illustrated the usage of Zonal Statistics[6] tool in QGIS 3.16.

Figure 4. Zonal Statistics Tool in QGIS



6 Zonal statistics in GIS is a tool that calculates statistics of a raster layer for each feature of an overlapping polygon vector layer. User Mannual. QGIS.org. "Raster Analysis using Zonal Statistics" June 08, 2021, www.docs.qgis.org/3.16/en/docs/user_manual/processing_algs/qgis/rasteranalysis.html#zonal-statistics

4 Usability of Urban Heat Island maps in policymaking

Various concepts exist around developing and using geographic data for evidence-based decision support systems. Ranging from regional climate analysis to deriving area-specific vulnerable heat spots using LST, city administrations can monitor and regulate impact of urban development activities. There are many natural processes that directly and indirectly are impacted by rising surface temperatures in urban areas. Use of urban land cover change analysis along with surface temperature, air temperature and vegetation indices can aid in monitoring the UHI. All these indicators affect the microclimate of the area pushing the demand for energy to be used in refrigeration or air conditioning consequentially compromising public health, urban socio-economics, and thus the development goals. As a result, it is imperative to identify these hotspots in the cities and implement solutions to counteract their impacts.

4.1 Case in point: City-level land surface temperature analysis using LandSat 8 imagery

Owing to the objective of the project that is to empower cities with knowledge and insight on using remote sensing as a tool to investigate their urban heat islands – A subsequent study to retrieve the land surface temperature values for three cities is conducted using the methodology explained in aforementioned sections. Using LandSat 8 imagery from 2014 to 2021, urban hotspots and LST trends were examined for Coimbatore, Kochi and Bhubaneswar. The analysis comprises of four parts which include the creation of 1) a series of static heat maps representing LST for specific dates for which the imagery was acquired, 2) a series of ward-wise average LST maps for the same dates, 3) a linear fit trend map showing change in LST from 2014 to 2021, and 4) micro-level/site-level analysis using google earth imagery for selected locations in each of the three cities. While all three are tropical in nature, their distinct geography, land use combinations and urban setting have resulted in varying causes of heat islands being observed. The following text provides a summary of the analysis conducted along with the representation of results accumulated.

There are many natural processes which directly and indirectly are impacted by rising surface temperatures in urban areas.

The analysis has identified hotspots with a rise in LST of more than 1 °C in Coimbatore, more than 0.9 °C in Kochi, and more than 0.8 °C in Bhubaneswar between 2014 to 2021. Additionally, the ward-level analysis syncs LST values with administrative boundaries to make them usable in development regulations and zonal/local area plans. Thirdly, the site-level analysis has brought to light specific examples of land use – land cover change over the years which has contributed to a rise in LST. Reduction of green and blue land cover for the construction of industrial areas, housing complexes, transport hubs, etc., built form and urban fabric in all three cities are some examples of observed causes behind the conspicuous hotspots. Refer to the following figures for additional details., the results eminently establish that areas with healthy vegetation and water bodies tend to not get warmer despite being pushed by extreme heat events such as heatwaves or peak summers and are in fact relatively much cooler thus influencing the overall heat index of the region. Therefore, the results outlay a guiding path to a balanced amalgamation of green and blue landscape that may help urban local bodies to keep a check on the land surface temperature without compromising on the city's environmental health and urban growth.

Figure 5. Land Surface Temperature Trends along with details of major hotspots in the city - Coimbatore

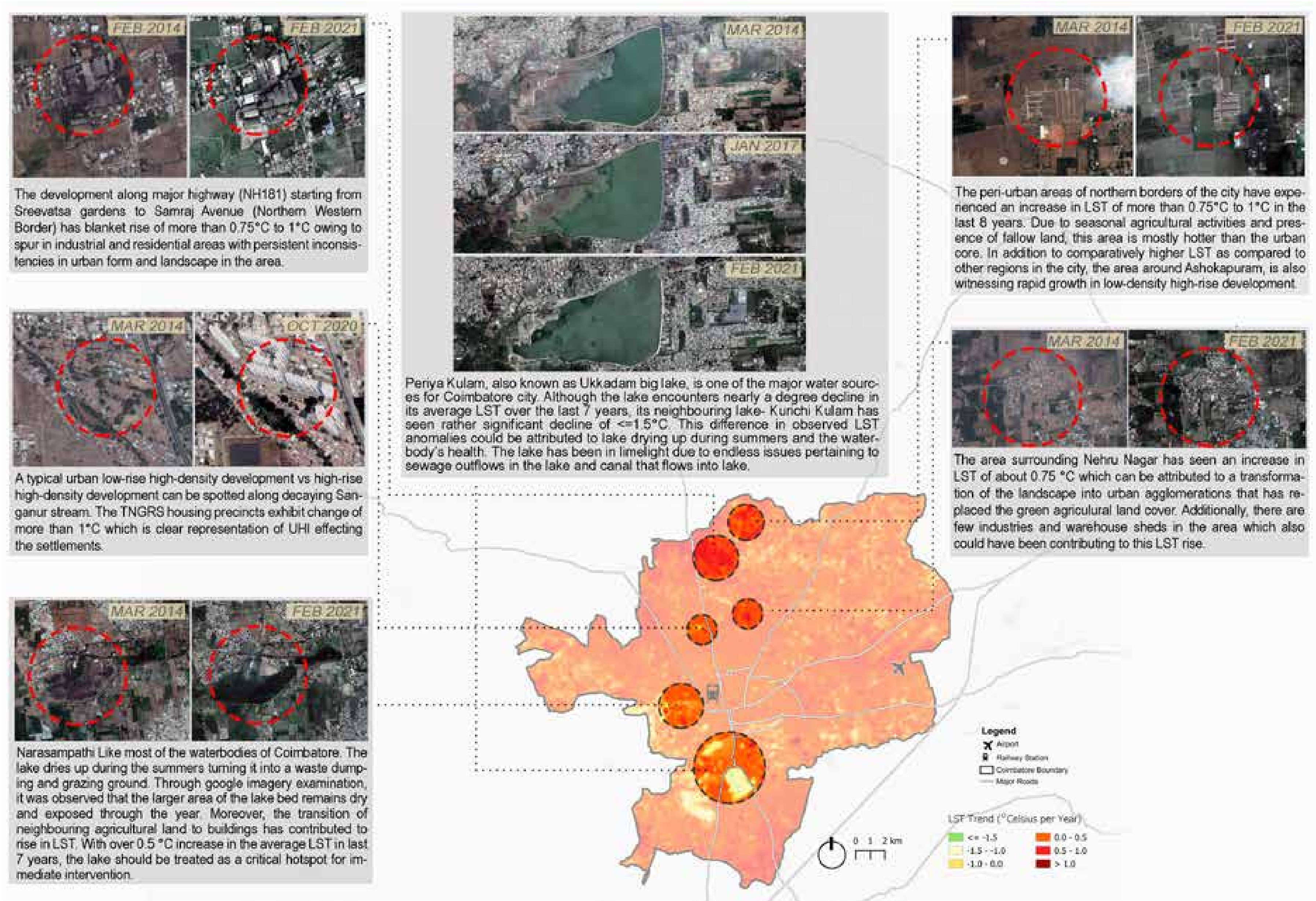


Figure 6. Land Surface Temperature Trends along with details of major hotspots in the city - Kochi

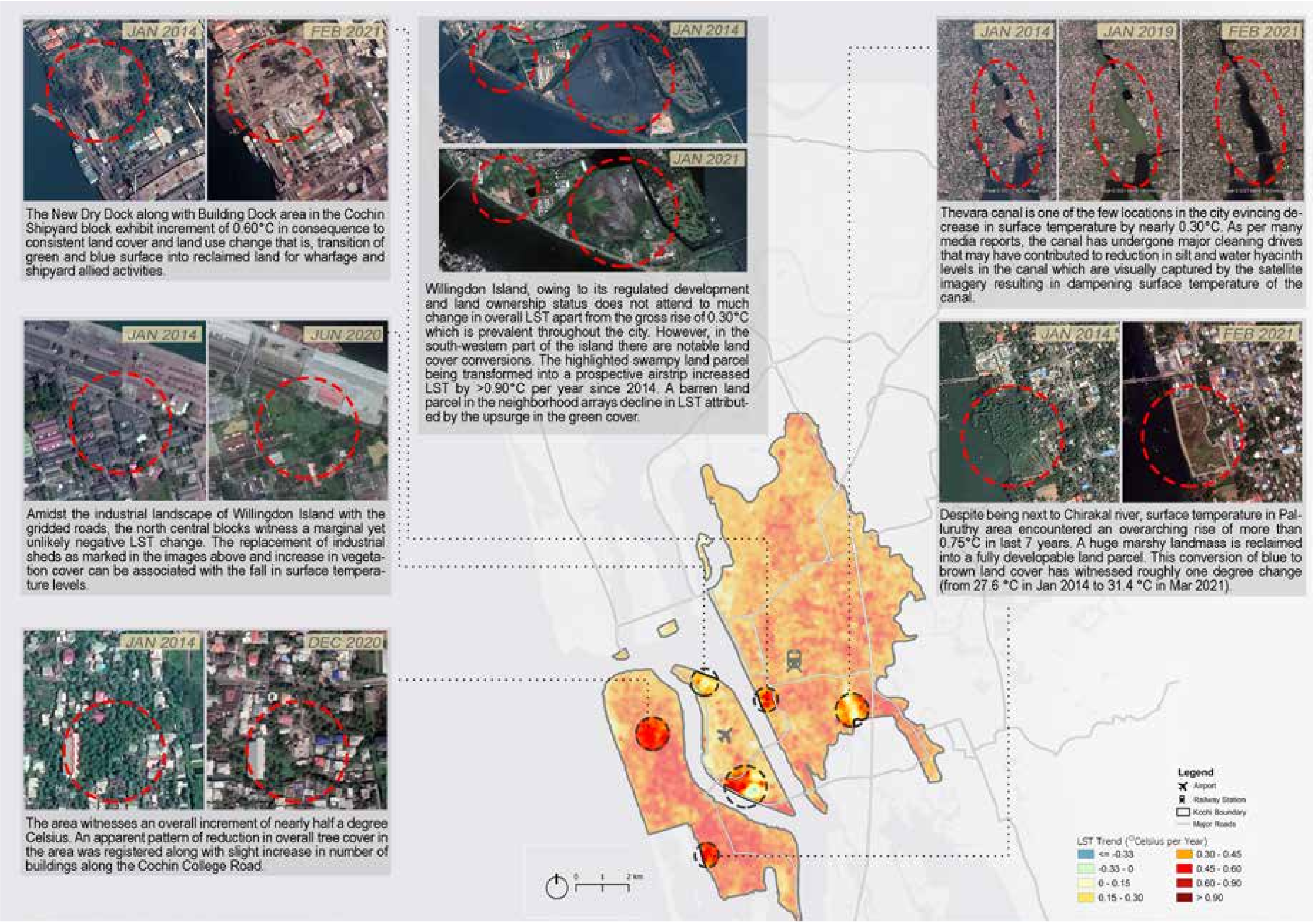
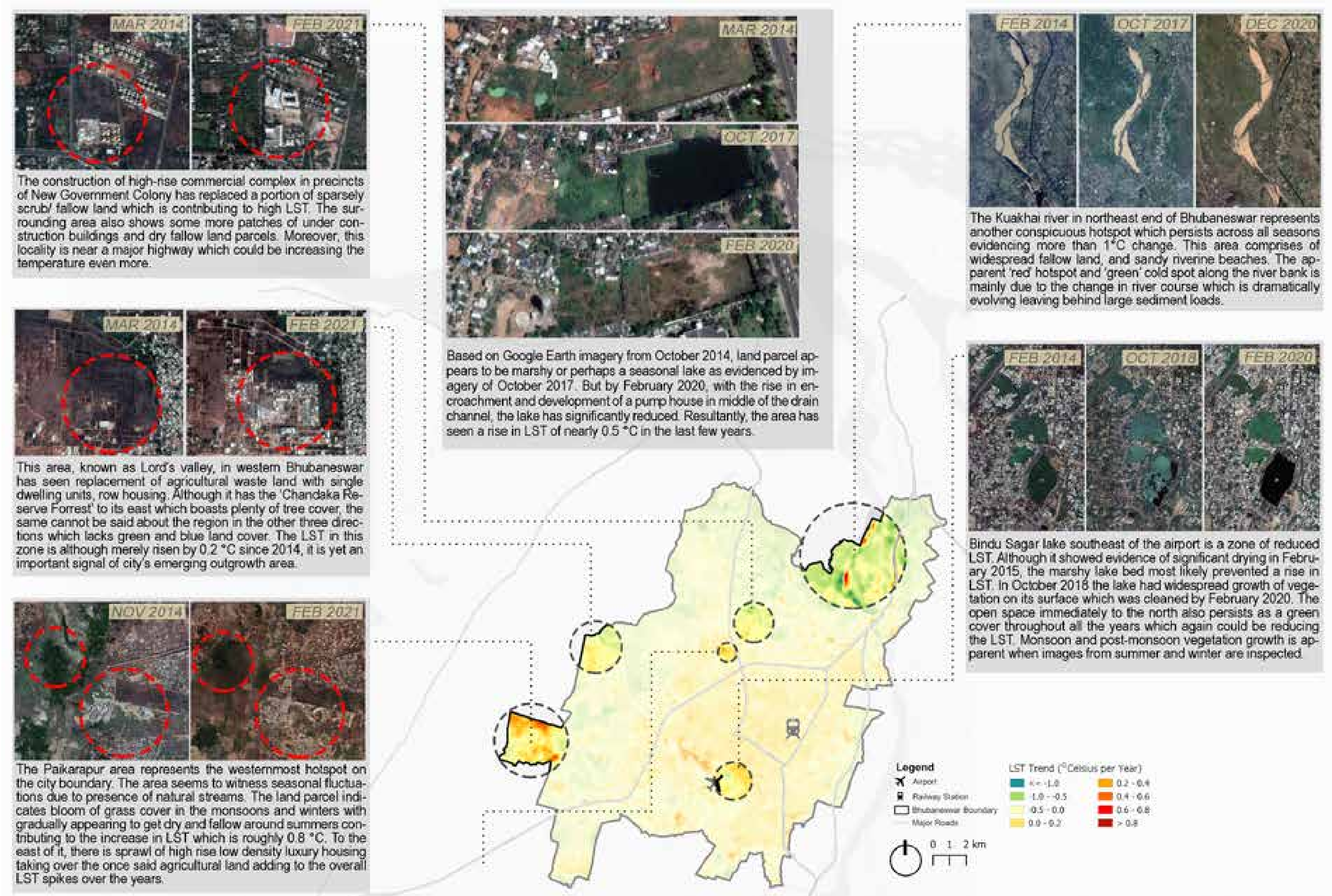


Figure 7. Land Surface Temperature Trends along with details of major hotspots in the city - Bhubaneswar



4.2 Way Forward

Overlaying LST hotspots in urban areas with land use data often result in insightful findings of the built-scape transformation and can help cities develop mechanisms to manage the local climate. While in-situ temperature monitoring solutions might not be a convenient solution for all, the thermal remote sensing tools provide an effective fix for surveilling heat sink and heat budgets in a city. With the number of Indian cities developing their Climate Resilient City Action Plans (CRCAPs), heatwave management plans, and launch of ClimateSmart Cities Assessment Framework (CSCAF), etc. LST supervision can allow cities to create adaptive policy frameworks to combat climate change. To dampen the urban heat island zones in the cities, administrations can use various green cover management strategies aligned with stormwater and waterbody development projects. Within the existing CRCAP methodology[7], LST retrieval can be embedded to phase 1 (Analyse) and phase 3 (Accelerate). Under phase 1, step 3, tool 3.2 (ICLEI, 2017), cities can adopt LST retrieval to identify fragile urban zones and thermal hotspots based on the likelihood of occurrence of other climatic risks as well. Similarly, LST retrieval and a thorough UHI impact analysis can also be included in the ClimateSmart Cities Assessment Framework, a first-of-its-kind city-level analysis framework on climate-sensitive parameters specially tailored for Indian cities launched by MoHUA in 2019. CSAF's score aggregation of 'Urban Planning', 'Green Cover & Biodiversity' sector, specifically Indicator 1: Rejuvenation & Conservation of Water Bodies & Open Areas can be corroborated using the LST trends to develop a deeper understanding of the micro-climatic conditions of the city. It will empower cities with information on climate fragility, location, vulnerable population and habitats, building surface materials, and heat intensity of activities within the identified hotspots.

Plenty of case studies, research literature, policy reviews, etc. available around the globe detail the success and failures of various urban thermal stress combat strategies empowering city administrations with learnings and options to tailor their own blueprint of mitigating heat island effects. Some proven techniques include spreading awareness regarding extreme heat risks, building cooling centers and spray parks in communities, installing green roofs, auditing the tree cover in the city, creation of urban forests, and cool roofing by painting the roofs with reflective materials, etc. (TARU, 2021). However, the thermal environment in a tropical climates that experiences high latent heat fluxes, is deeply affected by the heterogeneous nature of urban settings (Priyadarsini, 2020). Moreover, for developing tropical/ sub-tropical cities or countries where exposure, sensitivity, and a lack of adaptive capacity to extreme heat are likely to coincide with socio-economic needs, the challenges posed by heat islands are manifold. Therefore, any heat alleviation strategies including tree planting or land-use planning should be cautiously adopted according to the geometry and scale of city blocks, micrometeorological elements, the orientation of the streets, and even narrowed to individual housing units where radiation in the form of solar gain is influenced by factors including building color, size, facade and shading (Khan, Chatterjee, & Weng, 2021).

[7] The Climate Resilient City Action Plan (CRCAP) methodology is tailor made for Local Governments/ ULBs, providing step by step guidance for the development of a climate resilient city action plan. It consists of a wide range of tools and guidance notes to support ULBs to deliver effective local climate action. CapaCITIES India.org. "Climate Resilient City Action Plan (CRCAP)" 2016, https://www.capacitiesindia.org/crcap/

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Notes

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